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An understanding of the concepts of atoms and molecules is fundamental to the learning of chemistry. Any misconceptions and alternative conceptions related to these concepts which students harbor will impede much further learning. This paper identifies misconceptions related to the fundamental characteristics of atoms and molecules which Grade 12 students hold. Data were obtained by administration of semi-structured individual interviews to a stratified random sample of 30 students of differing abilities and backgrounds in science. Fifty-two misconceptions were observed and are reported. These are grouped into 11 categories relating to structure, composition, size, shape, weight, bonding and energy of molecules and structure, shape, size, weight and animistic perceptions of atoms. Many of the misconceptions identified parallel historical ideas of science. (Author)

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AN INVESTIGATION OF GRADE 12 STUDENT S' MISCONCEPTIONS RELATING TO FUNDAMENTAL CHARACTERISTICS OF MOLECULES AND ATOMS

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ABSTRACT

An understanding of the concepts of atoms and molecules is fundamental to the learning of chemistry. Any misconceptions and alternative conceptions related to these concepts which students harbor will impede much further learning. The present paper identifies misconceptions related to the fundamental characteristics of atoms and molecules which Grade 12 students hold. Data were obtained by administration of semi-structured individual interviews to a stratified random sample of thirty students of differing abilities and backgrounds in science. Fifty-two misconceptions were observed and are reported. These are grouped into eleven categories relating to structure, composition, size, shape, weight, bonding and energy of molecules and structure, shape, size, weight and animistic perceptions of atoms. Many of the misconceptions identified parallel historical ideas of science.

INTRODUCTION

Researchers and educators writing from a variety of theoretical perspectives have suggested that the most important things that students bring to their classes are their concepts. This includes writers from the cognitive perspective (Ausubel, Novak, and Hanesian, 1978), the developmental perspective (Piaget, 1964; Shayer and Adey, 1981), the behaviorial perspective (Gagne, 1970), the constructivist perspective (Driver and Oldham, 1986; Osborne and Wittrock, 1983), and others. Hence, knowledge of learners' conceptions and misconceptions is of particular interest and may be of particular importance to educators.

In recent years, the science education literature has been replete with reports of studies relating to the identification, explanation, and amelioration of students' difficulties in understanding science concepts. Such difficulties have been characterized in various ways, for example, as misconceptions (Fisher, 1983), alternative frameworks (Driver and Easley, 1978), intuitive beliefs (McCloskey, 1983), preconceptions (Anderson and Smith, 1983), spontaneous reasoning (Viennot, 1979), children's science (Osborne, Bell, and Gilbert, 1983), and naive beliefs (Caramazza, McCloskey, and Green, 1981). In the present paper the term misconception will be used and is defined as by Cho, Kahle, and Nordland (1985) to include *"any conceptual idea whose meaning deviates from the one commonly accepted by scientific consensus."*

A review of the research relating to students' misconceptions of science concepts reveals that these misconceptions have many common features. They are often strongly resistant to traditional teaching and form coherent, though mistaken, conceptual structures (Driver and Easley, 1978).

Misconceptions cover a large range of science concepts (Gilbert and Watts, 1983), and some have historical precedence in that some erroneous ideas put forth by students today mirror ideas espoused by past leaders in the field. They may arise prior to formal instruction as a result of the variety of contacts students make with the physical and social world (Strauss, 1981), or as a result of interaction with teachers (Gilbert and Zylbersztajn, 1985), or from textbooks (Cho, Kahle, and Norland, 1985).

Studies in which students' misconceptions are described cover a wide range of areas. Studies in physics include those related to force (Minstrell, 1982; Gardner, 1986); light (Anderson and Karrquist, 1983); energy (Duit, 1983; Watts, 1983); and electricity (Shipstone, 1984). Studies in biology include reference to misconceptions relating to topics such as photosynthesis (Wandersee, 1983); circulatory systems (Arnaudin and Mintzes, 1985); translation (Fisher, 1985); and food-webs (Griffiths and Grant, 1985). Reports relating to the area of chemistry include: chemical reactions (Anderson, 1986); chemical equilibrium (Hackling and Garnett, 1986); the mole (Duncan and Johnstone, 1979); and the particulate nature of matter (Novick and Nussbaum, 1981). In chemistry, the range of concepts which has been investigated is not extensive, and further elaboration seems appropriate.

Chemical educators would generally agree that understanding the concepts of atom and molecule is fundamental in the learning of chemistry. Such understanding is essential to the learning of other concepts such as chemical bonding, chemical reactions, ions, and states of matter. The present study focuses upon High School students' understanding of the nature of atoms and molecules.

As part of a pre-pilot study, 10 high school students who were taking courses in chemistry were interviewed to probe their understanding of the concepts of atoms and molecules. Several misconceptions were identified: *"Electrons have no mass, just a charge"*;

"All the atoms in a molecule are the same"; "There is only one kind of atom"; and "Protons have a mass of one gram". Given the nature and number of misconceptions from this group, these findings supported the need for further study.

Other studies which have investigated students' conceptions of matter indicate that students harbor misconceptions relating to matter in general and hold particular misconceptions relating to molecules and atoms. Students may have a primitive continuous outlook on the physical world, as opposed to the accepted particulate model (Novick and Nussbaum, 1978; Doran, 1972). Osborne and Freyberg (1985, p.56) report that students, even after instruction, are *"still confused about the multiplicity of terms they have been exposed to, for example, particles, atoms, molecules and nuclei--and their interrelations."* Cros and Maurin (1986), in a study involving first-year university students, reported that the constituents of the atom were *"either totally unknown or poorly perceived"*. Dow, Auld, and Wilson (1978) reported that a popular misconception among 12 to 13 year old students was that molecular diameter decreases progressively from solid to liquid to a gas for a given substance. Another study by Brook, Briggs, and Driver (1984) showed that students have a tendency to transfer changes in macroscopic properties to the microscopic level. For example, students suggested that particles can melt, and they can become hot or cold.

Numerous reasons have been advanced to explain why students might have problems understanding the characteristics and functions of atoms and molecules. Osborne and Cosgrove (1983) suggest that scientific models of the atom as typically taught can appear to be abstract, and hardly, if at all, relatable to everyday experience. Ault, Novak, and Gowin (1985) describe the concept of molecule as having *'nearly limitless complexity'*. They suggest that while students may be able to grasp the abstract meanings of molecules, at some level, their conceptual patterns may be imaginative and unconventional. Finally, textbooks often present conflicting models of the atom which may lead to confusion for many students. Findings from related studies have provided direction for developing the types of questions contained in the interview guide of the present study.

RESEARCH QUESTIONS

The following questions were addressed:

1. Which concepts relating to molecules and atoms are misunderstood and therefore limit students' understanding of the topics?
2. How do misconceptions differ among students who have differ in level of participation in science and academic ability?

PROCEDURE

The process of collecting information took place over two phases: a pilot study which involved interviewing six students using a partially structured interview guide, and a final group of interviews which used questions from the developed interview guide. Subjects were selected by stratified random sampling and grouped as Academic-Science, Academic-Non-Science, and Non-Academic Non-Science according to their academic average and their participation in science. Pilot study subjects did not participate in the final study. The primary purpose of the pilot study was to produce a refined interview guide.

Each interview session, which typically took about 30 minutes, was tape-recorded and transcribed for further analysis. Interviews were held during school hours, and took place in a sequence which was determined primarily by the availability of each subject. The data collected from the final study were fully analyzed using a three stage process which will be described later.

THE INTERVIEW GUIDE

The interview guide consisted of two major groups of questions, one relating to molecules and the other to atoms. In the first category, questions were asked relating to the structure, composition, size, shape, weight, bonding, and energy of molecules using a water molecule as the example. The second group of questions focused on the structure, shape, size, weight, and perceived animism of atoms. In addition to answering questions verbally, students were asked to illustrate their understanding of structure, bonding and atoms by making a sketch. The questions relating to molecules and atoms were separated as much as possible to avoid

confusion between them. A balance of open and closed questions, and simple and difficult questions were used to maintain pupil confidence and clearly establish students' ideas.

SAMPLE

The sample consisted of 30 Grade 12 students drawn from ten High Schools in three school boards located on the Avalon Peninsula of Newfoundland, Canada. The interviews were conducted with eighteen males and twelve females aged 16 to 18. The sample was divided into three sub-groups of ten students each. The sub-groups were labelled Academic Science, Academic Non-Science, and Non-Academic Non-Science. 'Academic' subjects had an overall academic average of 75 percent or higher, and 'Science ' subjects had completed or were attempting to complete three academic High School science courses such as Chemistry, Biology, or Physics.

ANALYSIS AND REPRESENTATION OF THE DATA

The transcribed tapes served as the starting point for the analysis of the interview data. The analysis followed a three-phase process. The aim of the first phase was to establish a conceptual inventory for each student interviewed. The transcripts were analyzed to identify each student's misconceptions, which were then placed in appropriate, predetermined, content-oriented categories. A combination of all of the ideas for each of the content domains formed the *"conceptual inventory"* for each student. The second phase of the data analysis involved identifying and organizing the most common misconceptions according to category and prevalence for each group of students. The final phase of the data analysis involved a descriptive summary of the overall findings for each of the content areas. Included are extracts in the form of quotes from transcripts, and comments about the ways in which the common misconceptions differ from orthodox conceptions. The three sub-groups Academic Science, Academic Non-Science, and Non-Academic Non-Science were labelled as A, B, and C respectively.

RELIABILITY AND VALIDITY

Traditionally, science educators have been convinced of the need to establish the validity and reliability of their data, and have developed generalized techniques to ensure this. However, like other naturalistic techniques, interview data pose unique problems. Science educators have not overcome these problems. We concur with the position that *"In the present state of the research on conceptual frameworks reliability is a rather neglected issue, despite its importance."* (Hoz, 1983, p.161), and that the reliability of an interview is *".....seldom mentioned, let alone estimated."* (Shavelson, Webb and Burstein, 1986, p.80) In the present study we attempted to address the problem in several ways. One of the authors (Preston) conducted the interviews from a semi-structured protocol, with guidance and feedback from the other author. Hence consistency of administration was ensured. Consistency of response by individual subjects was established by including repeat questions, although there are clearly limits to the extent to which this can be done without disrupting the flow of the interview. We observed repeat consistency of over 90 percent. Internal validity was established by refining the interview guide over a number of pilot administrations, with feedback from several independent science educators throughout. External validity was controlled by stratified random sampling from a group of students representative of the target population. To use terms drawn from the naturalistic paradigm, we took steps to ensure that our findings are dependable, credible, transferable, and confirmable. (Guba and Lincoln, 1981)

FINDINGS

The following results represent a gradual reduction of the total information for the purpose of relating it specifically to the original research questions. For each of seven content areas relating to molecules and four relating to atoms, information is presented which indicates the particular misconceptions identified, and their prevalence. This information is summarized in Appendix 1, which is presented at the end of the paper for convenience. The content areas relating to molecules are discussed first, with content areas relating to atoms following.

A general pattern is followed. The objectives of the questions are first introduced, followed by a description of the misconceptions revealed, including excerpts from the interviews to illustrate the misconceptions. Some suggestions are made to indicate possible sources of misconceptions and, where appropriate, misconceptions are related to previously accepted but now discarded notions in science. In each case the frequency of misconception for each sub-group is indicated in parentheses.

Structure of Molecules

The first six questions of the interview guide were meant to elicit students' understandings of the structure of molecules. Subjects were first asked to sketch what they would see if they could look at a molecule of water under a microscope so powerful that they could see all the details of one individual molecule. Subjects were asked to do this for water molecules in all three phases, and they were then asked to explicate the parts of the molecules which they drew.

About one-quarter of the subjects (1A, 3B, 4C) held Misconception 1.1, that a water molecule resembles a closed figure with no definite shape. Others (1A, 3B, 3C) believed that a water molecule is spherical with particles spread throughout (MC 1.2). These subjects suggested a wide range of ideas to indicate the nature of those particles, including reference to chlorine, oxygen, hydrogen, and 'organisms'. The bulk of the students holding these misconceptions were from the Academic Non-Science and Non-Academic Non-Science groups.

One third of the subjects (7A, 1B, 2C) believed that water molecules are composed of two or more solid spheres (MC 1.3). Six of these subjects (5A, 1C) believed in three solid spheres. Of particular interest here is the fact that most of the subjects holding this misconception were from the Academic-Science sub-group, which suggests that this misconception arose from some aspect of the academic instructional treatment. The use of three-dimensional diagrams or the use of ball and stick models seem likely candidates as being more likely to be encountered in an academic science course.

Composition of Molecules

The next group of questions were meant to elicit students' conceptions relating to the composition of molecules. Subjects were asked to describe what water is made up of, how many atoms might be found in a molecule of water, and whether and how the molecules within different phases would differ in terms of the kind and number of atoms.

Forty percent of the subjects (2A, 4B, 6C) held Misconception 2.1, that water molecules contain components other than oxygen and hydrogen. Subjects suggested that water molecules are composed of water, air, chlorine, nitrogen, or minerals. A common view that water molecules from tap water contains impurities was typically accounted for by the suggestion that *"... water has to go through many pipes before it reaches your tap so therefore it adds on more things"* (A). Many students indicated that the impurities would stick to the outside of the molecules.

Eleven subjects (1A, 5B, 5C), including one half of those in Group B and one half in Group C, held Misconception 2.2 that water molecules are not all composed of the same atoms. Responses suggested that the composition depends on the size, the temperature, or the phase of the molecules. One group B subject suggested that the composition of the water molecules in the steam would be different *"...because it's heated, it's adding more oxygen."* A Group C subject suggested that the size of a molecule affects its composition because *"If they (molecules) are smaller they cannot hold as many parts."*

Subjects were also asked, *"How many atoms would you find in a molecule of water?"* Eleven subjects (2A, 5B, 4C) believed that water molecules contain more than three atoms (MC 2.3). Responses such as: water molecules contain *"...hundreds of thousands of atoms;* and *"...you would find millions of atoms in a molecule."*, were not unusual. One subject from each group held Misconception 2.4, that water molecules contain less than three atoms.

Misconception 2.5, that water molecules contain different number of atoms, was identified from responses to the question, *"Would all water molecules have the same number and kind of atoms?"* One-third of the subjects (1A, 6B, 3C) held this belief. Most subjects holding Misconception 2.5 believed that water molecules from the solid phase (ice) contain the

most atoms. One subject explained that *"As molecules go from ice to steam they lose atoms."* (B), and another suggested that molecules from the solid phase have the highest number of atoms because *"...atoms in the ice are packed closer together."* (C)

Academic Science students had a good understanding of the composition of water molecules and collectively showed few misconceptions. In contrast the Academic Non-Science and Non-Academic Non-Science groups showed substantial misunderstanding of the composition of molecules.

Size of Molecules

A third group of questions were directed towards eliciting students' conceptions relating to the size of molecules, using water molecules as a reference. Eight misconceptions were exhibited.

Subjects, were first asked. *"How big do you think a molecule of water is? Try to compare it with something?"* One-half of the subjects from each group held Misconceptions 3.1, that a water molecule is 'macro' in size, where the term 'macro' characterizes a wide range of responses which represent gross overestimates of the size of a molecule. Examples include suggestions that water molecules are *"As big as a germ ..."*(A), *"The size of a point on a pencil, like a dot."* (C), and are the size of *"A speck of dust"* (C). This misconception may result from typical school experiences in which students look at illustrations and handle concrete models of molecules without appropriate reference to scale. Conversely, a few subjects (2B, 2C) held Misconception 3.2, that a water molecule is the smallest indivisible entity.

A very prevalent misconception (MC 3.3) held by more than three-quarters of all subjects, (4A, 10B, 9C) was the belief that water molecules within a phase may have different sizes. Despite the commonality of this misconception, subjects offered very few coherent explanations.

The next group of questions asked subjects to compare the size of water molecules across the three phases and to account for any differences. Responses were classified as Misconceptions 3.4, 3.5, 3.6, and 3.7, respectively. Of these, Misconception 3.4, that water molecules from the solid phase (ice) are the largest, was the most common (2A, 5B 5C), being

held by 40 percent of the sample. The most typical explanation offered was that *"... when water freezes it expands"*. In contrast to Misconception 3.4, one-sixth of the subjects (3A, 2C) held Misconception 3.5 that water molecules from the solid phase (ice) are the smallest.

Still, others (4B, 6C) held Misconceptions 3.6, that water molecules from the gaseous phase (steam) are the smallest, a misconception which is similar to that reported by Dow, Auld and Wilson (1978) who concluded from student drawings depicting particle size across the states that subjects generally drew particles in the liquid and gaseous state smaller than those in the solid state. The final misconception observed in this set (MC 3.7) was that water molecules from the gaseous phase (steam) are the largest (3A, 1B, 3C). The most typical explanation was that *"... the heat makes them (molecules) expand"* (A).

In general, most subjects believed that the size of a water molecule is determined by which phase it is in. The only common explanation is reflected in Appendix 3 as Misconception 3.8, namely that the size of a water molecule depends on its temperature (4B, 1C).

Shape of Molecules

The questions from this category were directed towards revealing subjects' misconceptions relating to the shape of molecules, using water molecules as a reference. Using the sketches which they drew during the questions on molecular structure, subjects were asked whether the structures were flat or three-dimensional, whether all the molecules from within each phase were the same shape, as well as what factors affect the shape of a molecule.

Six subjects (3B, 3C) held Misconception 4.1, that water molecules are flat. Seven subjects (1A, 2B, 4C) held Misconception 4.2 that water molecules have different shapes depending on what phase they are in. Still others (3A, 8B, 6C) suggested that water molecules within a phase may have different shapes (MC 4.3), a view advanced three and a half centuries ago by Descartes.

Subjects suggested three major factors to explain differences in shapes of molecules both between phases and within phases. Nearly one-half of the subjects (3A, 6B, 5C) held Misconception 4.4, that the temperature may affect the shape of the molecule. Another common misconception (MC 4.5) was the notion that the shape of a container will affect the shape of the

molecules (4B, 1C). A typical explanation included *"... because liquid takes the form of the container ... the molecules take the shape of what it's held in " (C).* Another subject suggested that all the molecules in an ice cube are square because of the shape of an ice cube. Again this is a view held in earlier times. For example, in 1807 Havy suggested that compounds shaped as cubes are composed of integrant particles in the same shape (Crosland, 1971).

Finally, three subjects from group A, held Misconception 4.6, that pressure may affect the shape of a molecule. This misconception is of interest in that it was held only by students in the top group, although there is no apparent reason for this.

Weight of Molecules

The questions from the 'weight' category of the interview guide were meant to elicit subjects' conceptions relating to the weight of a water molecule. Specifically, subjects were asked to compare the weight of a water molecule within each of the three phases of matter with something of their choice, to indicate from which phase the molecules are heaviest if there is a difference, and to explain why. The most common misconceptions are represented in Appendix 1.

Subjects generally tended to grossly overestimate the weight of water molecules. Nearly half (1A, 6B, 7C) exhibited Misconception 5.1, that water molecules are heavy enough to be physically weighed. Typical responses included: *"A molecule weighs about the same as a fly's leg" (B); "Light as a piece of dust" (B); "Light as a feather" (B).*

Thirteen subjects (3A, 4B, 6C), held Misconception 5.2, that water molecules within a phase may weigh differently. A variety of explanations were advanced. One subject said that *"When the steam goes through the air it (molecules) can pick up warm particles ... and some molecules can pick up more particles than others, so they can weigh differently" (C).* Another subject suggested that water molecules from tap water may weigh differently *"... depending on the amount of impurities in the molecules"* (A).

One-half of the subjects (2A, 6B, 7C) held Misconception 5.3, that water molecules from the solid phase (ice) are the heaviest, and Misconception 5.4, that water molecules from the gaseous phase (steam) are the lightest. One subject explained that molecules from the ice are

the heaviest because "*... they are closer together*" (B), while another suggested that "*... because ice is dense its molecules must be heavy*" (C). Views were also advanced views to account for Misconception 5.4. A third suggested that water molecules from the gaseous phase are the lightest "*... 'cause it rises*" (C), while another suggested that the molecules in the gaseous phase are lightest because "*... they are farther apart.*" Both Misconception 5.3, and Misconception 5.4 were considerably more prevalent for subjects from Group B and Group C then for subjects from Group A. A few subjects (2A, 2B, 1C) suggested that the size of a water molecule affects its weight (MC 5.5).

Bonding of Molecules

The purpose of the next series of questions was to identify subjects' conceptions relating to the bonding of molecules. More specifically the questions asked how molecules are held together, what exists between the molecules, and what happens in terms of bonding as molecules go through phase changes. The questions from this category used water molecules from ice as the starting point of discussion.

Subjects were first asked to sketch what they would see if they could take half a dozen molecules from ice and look at them under a microscope so powerful that they could see all six molecules. The most typical sketch was that showing the molecules touching one another with no space between the water molecules. This view represents Misconception 6.1, which was held by fourteen subjects (5A, 6B, 3C). The sketches are consistent with the findings of Novick and Nussbaum (1978) who reported that students have a primitive continuous outlook on the physical world as opposed to the accepted particulate model. For subjects holding this misconception, the concept of bonding may not mean a force of attraction. A second misconception (MC 6.2), namely that water molecules in ice are not bonded in any pattern or arrangement, was exhibited by one-third of the sample (3A, 3B, 4C).

Subjects were next asked to explain how the molecules are held together. A common misconception (MC 6.3), was that water molecules are held together by something external to the molecules. Typical responses were: "*... there's stuff like ... there's certain things that keep*

them together" (A); *"... some kind of fusion, ... heat would keep them together"* (A); *"maybe it's the force of gravity"* (B); or *"air pressure from the outside"* (C).

Finally, subjects were asked to explain why molecules separate farther apart when going from ice to liquid to steam. Four subjects (2A, 2C) suggested that heat causes molecules to expand leading to their separation during melting, (MC 6.4).

Energy of Molecules

The final group of questions relating to molecules focused upon the energy of molecules. Subjects were asked to name the phase of matter in which molecules move the fastest and slowest, to give reasons to account for differing speeds, and finally to suggest what happens when heat is added to molecules.

In relation to molecular speed, most subjects correctly indicated that all molecules move, and that the ones in the gaseous phase have a higher average speed than those in other phases. However, a few subjects (3A, 2C) suggested that all water molecules within each phase move at the same speed (MC 7.1).

A few subjects expressed one or other of two misconceptions when asked to explain why some water molecules move faster than others. The first was that the speed of a molecule is determined by its size (MC 7.2). One subject explained, *"I guess (some molecules move faster than others) because some are probably smaller"* (A). The other (MC 7.3), was that some molecules move faster than others because the more space a molecule has to move the faster it will move (2B, 1C). A typical response was, *"space, ... some might have more space to move, therefore they move faster"* (C).

The final question from this category asked subjects to explain what happens to water molecules in ice when heat is applied. Two misconceptions were revealed from their responses. One was that heat causes water molecules to expand (MC 7.4). The other was that heat causes water molecules to break down (MC 7.5).

The remaining questions related to atoms. Generally, fewer misconceptions were uncovered than for questions relating to molecules.

Atomic Structure/Shape

The purpose of the questions from this category was to identify subjects' misconceptions relating to the structure and shape of atoms. No particular atom was used as a reference. Subjects were asked to illustrate their ideas through a sketch, where possible.

Subjects were first asked to sketch what they would see if they could take one atom and look at it under a microscope so powerful that all the details of the atom could be seen. These sketches revealed three misconceptions. The first (MC 8.1) was that an atom resembles a sphere with components inside (1A, 3B, 4C). A typical sketch resembled a circle with dots inside to represent components. The second misconception, (MC 8.2), was that an atom resembles a solid sphere (3A, 1B, 4C). A possible source of this misconception could be exposure to texts where solid spheres are used to represent atoms. The third (MC 8.3) was that an atom resembles several dots or circles, randomly distributed (3A, 3B). Overall, these misconceptions were observed fairly equally for subjects in all three groups.

Next, subjects were asked to identify any smaller components of atoms if in fact they thought there were any. Most subjects indicated that atoms do contain smaller components, but no subject suggested that atoms were composed of anything other than electrons, neutrons, and protons. Four subjects (2A, 2B) suggested that electrons move in orbits (MC 8.4), a belief reported elsewhere to be common among first-year university science students (Cros and Maurin, 1986).

Two other misconceptions relating to the structure/shape of atoms were observed. First, Misconception 8.5, was that atoms are flat. Although only two subjects held this misconception it may be of some significance in that it appears to indicate the influence of two dimensional text on what should be three-dimensional thought. The second (MC 8.6) was the belief that matter exists between atoms. When asked to describe what there might be between the atoms, the most typical response was *"air"*. Other responses included *"Different materials ... gases ... oxygen"* (B), and *"... there are electrical charges"* (C). A total of fourteen subjects (3A, 5B, 6C) held Misconception 8.6. Subjects generally had difficulty conceptualizing empty space between atoms.

Size of Atoms

The questions from the category 'size' asked subjects to describe the size of an atom, to compare the size of an atom with a molecule, and to give reasons why some atoms may be larger than others. The range and frequency of misconceptions relating to size of atoms were considerably less than those relating to size of molecules. However, the following were noted:

Subjects revealed two misconceptions when asked to compare the size of an atom with something of their choice. The first, Misconception 9.1, was that atoms are large enough to be seen under a microscope (1A, 2B, 2C). For example, one subject compared the size of an atom to a small piece of dust, while another suggested that an atom is "... *1/100th the size of the point on a pin*" (B). This overestimation of atomic size complements the findings of Ault, Novak, and Gowin (1985) who reported that students may see a molecule as the smallest piece of something which is directly observable, and of Anderson and Renstrom (1983) who suggested that students may view the atomic world as an extrapolation of the macroscopic world. A second misconception, Misconception 9.2, was that atoms are larger than molecules (1A, 2B).

Subjects were also asked if all atoms were the same size, and to explain any differences in size. Four subjects (1A, 3B) believed that all atoms are the same size (MC 9.3), while a further four (3A, 1B) believed that the size of an atom is determined primarily by the number of protons. Three of these subjects were from the Academic Science group.

The final question from this category asked if the size of an atom could change, and if so when would a change occur. Six subjects (1A, 3B, 2C) indicated that heat may result in a change of atomic size (MC 9.5). Further, all subjects who held this misconception suggested that adding heat to an atom would result in the atom expanding. A further five subjects (4A, 1B) believed that collisions between atoms may result in change of atomic size (MC 9.6). As in the case of Misconception 9.4, it is interesting that this misconception was held primarily by the academic science students, which suggests that the problem arises from some aspect of instruction.

Weight of Atoms

The questions from the *'weight'* category asked subjects if they thought all atoms weigh the same; and if not, to explain why some atoms weigh more than others; and to describe the weight of an atom by comparing it with something. Only one misconception was identified.

Most subjects said that atoms of different elements may have different weights, but a total of seven (2A, 2B, 3C) suggested that all atoms weigh the same (MC 10.1).

Subjects generally had difficulty describing the weight of an atom, and most resorted to comparing it with the weight of a molecule. Most subjects overestimated the weight of atoms. Typical responses included *"... as light as a feather"* (B), and *"... as light as air"* (A).

Animism

Questions from the final category were directed towards finding out if subjects believed that atoms are alive, and if so what evidence supports this belief.

More than one-half of the subjects (4A, 7B, 5C) believed that all atoms are alive (MC 11.1). This belief is consistent with the concept of hylozoism, which is the idea that all of nature is alive and sensitive, an idea that existed in the time of the Greeks and up to the seventeenth or even the eighteenth century. This finding is also consistent with the findings of Osborne and Freyberg (1985) who reported that children have an anthropomorphic view of the world. A related misconception, namely that only some atoms are alive (MC 11.2), was also revealed for a further three subjects (2A, 1B). One of these subjects exhibited the pre-Wohleriam view that *"... organic atoms* are alive".

These responses led to a further question asking subjects to explain why they believed some atoms are alive while others are not. Ten subjects (4A, 3B, 3C) suggested that atoms are alive because they move (MC 11.3). A typical response was, *"Within the atom there would be some movement, ... there would be movement of protons, or the atom itself would move"* (B).

CONCLUSIONS AND DISCUSSION

We have described the results of our study into high school students' understanding of the concepts 'molecule' and 'atom'. We found 52 misconceptions relating to these terms. Some of these misconceptions were not particularly widespread although they will be of interest to science teachers and others concerned with science education. Conversely, one-third or more of the sample shared nineteen misconceptions, while at least one half of the sample shared six of these. The latter included gross overestimation of molecular size, the beliefs that molecules of the same substance may vary considerably in size, that molecules of the same substance have different shapes in different phases, that molecules change weight when a substance changes its phase, and that atoms are alive. The former included the beliefs that water molecules are composed of two or more solid spheres; that water molecules are not all composed of the same atoms but rather contain other components and may contain more than three atoms; that molecules change in size when a phase change occurs, that molecules change shape with temperature change, that water molecules are heavy enough to be physically weighed and change weight when changing phase, that solid matter is continuous, that matter exists between atoms of a pure element and that atoms are alive because they move.

A finding that seemed paradoxical at first was that five misconceptions were exhibited more frequently by the academic science group than by the other two groups. Responses by group were as follows: Water molecules are composed of solid spheres (70% A, 15% B,C); pressure affects the shape of a molecule (30% A, 0% B,C); heat causes molecules to expand (30% A, 5% B,C); the size of an atom depends on its number of protons (30% A, 5% B,C); and atomic size is altered by collisions between atoms (40% A, 5% B,C). The differences between these proportions are all statistically significant ($p = .05$), but more importantly they seem to us to be educationally significant, and lend support to the contention that students' misconceptions sometimes arise from instruction.

Finally, we noted a number of responses which parallel ideas once held but now discarded by scientists, a finding consistent with the findings of other educational researchers.

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Appendix 1

MISCONCEPTIONS IDENTIFIED

Misconception	Prevalence A	B	C
THE STRUCTURE OF MOLECULES			
1.1 A water molecule resembles a closed figure with no definite shape.	1	3	4
1.2 A water molecule is spherical with particles spread throughout.	1	3	3
1.3 Water molecules are composed of two or more solid spheres.	7	1	2
THE COMPOSITION OF MOLECULES			
2.1 Water molecules contain components other than oxygen and hydrogen.	2	4	6
2.2 Water molecules are not all composed of the same atoms.	1	5	5
2.3 Water molecules contain more than three atoms.	2	5	4
2.4 Water molecules contain less than three atoms.	1	1	1
2.5 Water molecules contain different numbers of atoms	1	6	3
THE SIZE OF MOLECULES			
3.1 A water molecule is 'macro' in size	5	5	5
3.2 A water molecule is the smallest indivisible entity.	-	2	2
3.3 Water molecules within a phase may have different sizes.	4	10	9
3.4 Water molecules from the solid phase (ice) are the largest.	2	5	5
3.5 Water molecules from the solid phase (ice) are the smallest.	3	-	2
3.6 Water molecules from the gaseous phase (steam) are the smallest.	-	4	6
3.7 Water molecules from the gaseous phase (steam) are the largest.	3	1	3
3.8 The size of a water molecule depends on its temperature.	-	4	1
THE SHAPE OF MOLECULES			
4.1 Water molecules are flat.	-	3	3
4.2 Water molecules have different shapes depending on what phase they are in.	1	2	4
4.3 Water molecules within a phase may have different shapes.	3	8	6
4.4 Temperature may affect the shape of a molecule.	3	6	5
4.5 The shape of a container will affect the shape of molecules.	-	4	1
4.6 Pressure may affect the shape of a molecule.	3	-	-
THE WEIGHT OF MOLECULES			
5.1 A water molecule is heavy enough to be physically weighed.	1	6	7
5.2 Water molecules within a phase may weigh differently.	3	4	6
5.3 Water molecules from the solid phase (ice) are the heaviest.	2	6	7
5.4 Water molecules from the gaseous phase (steam) are the lightest.	2	6	7
5.5 The size of a water molecule affects its weight.	2	2	1
THE BONDING OF MOLECULES			
6.1 Water molecules in ice touch each other continuously leaving no space.	5	6	3
6.2 Water molecules in ice are not bonded in any pattern.	3	3	4
6.3 Water molecules are held together by something external to the molecules.	2	2	4
6.4 Heat causes molecules to expand leading to separation of molecules during melting.	2	-	2

Appendix Cont'd

		A	B	C
THE ENERGY OF MOLECULES				
7.1	Water molecules within each phase move at the same speed.	3	-	2
7.2	The speed of a molecule is determined by its size.	1	-	2
7.3	The more space a molecule has to move the faster it will move.	-	2	1
7.4	Heat causes molecules to expand.	3	1	-
7.5	Heat causes water molecules to break down.	-	1	4
THE STRUCTURE/SHAPE OF ATOMS				
8.1	An atom resembles a sphere with components inside.	1	3	4
8.2	An atom resembles a solid sphere.	3	1	4
8.3	An atom looks like several dots/circles.	3	3	-
8.4	Electrons move in orbits.	2	2	-
8.5	Atoms are flat.	-	2	-
8.6	Matter exists between atoms.	3	5	6
THE SIZE OF ATOMS				
9.1	Atoms are large enough to be seen under a microscope.	1	2	2
9.2	Atoms are larger than molecules.	1	2	-
9.3	All atoms are the same size.	1	-	3
9.4	The size of an atom is determined primarily by the number of protons.	3	1	-
9.5	Heat may result in a change of atomic size.	1	3	2
9.6	Collisions may result in a change of atomic size.	4	1	-
THE WEIGHT OF ATOMS				
10.1	All atoms have the same weight.	2	2	3
THE ANIMISM OF ATOMS				
11.1	All atoms are alive.	4	7	6
11.2	Only some atoms are alive	2	1	-
11.3	Atoms are alive because they move.	4	3	3